

METHOD FOR PRODUCING ACTIVE AND/OR SELECTIVE SOLID CATALYSTS FROM  
INORGANIC OR ORGANOMETALLIC MATERIALS

CROSS REFERENCE TO RELATED APPLICATIONS

Applicants claim priority under 35 U.S.C. §119 of GERMAN Application No. 198 43 242.9 filed 11 SEPTEMBER 1998. Applicants also claim priority under 35 U.S.C. §120 of PCT/DE99/02956 filed on 10 SEPTEMBER 1999. The international application under PCT article 21 (2) was not published in English.

The invention relates to a method for a fast and economic development of solid catalysts for heterogeneous catalytic reactions, occurring in processes in the chemical production and in the refinery technology as well as in environmental technology, by their parallel testing according to evolutionary methods.

The new development or improvement of heterogeneous inorganic solid catalysts is based on empirical expert knowledge and basic knowledge. Even though a comprehensive basic knowledge is available in regard to the function of individual inorganic components or compounds in the catalysis of certain partial reaction steps, which is of decisive importance for the catalyst development, it cannot be avoided in practice within the near future to prepare a large number of catalysts which are comprised of different active components or phases and to test them with regard to the catalytic action for the reaction in consideration.

For carrying out a predetermined reaction, several catalytically active phases will generally be available which are produced in a suitable manner and in a ratio of the active components to be empirically determined and which are combined in this way. The knowledge of physical, physical-chemical, and catalytic properties

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of solid bodies forms a rational basis for the selection of catalytically active materials in the catalyst development and improvement. Even when in an ideal situation the correct individual components or individual phases of the catalyst can be selected, it is required to determine the suitable mass ratio and preparation method.

From Advances in Catalysis 2 (1950) 81-104 an empirical search of promoters for inorganic multi-substance catalysts is known. In EP-A-0589384 an iterative method for the determination of parameter values is described in which the optimization strategy resides in that a binary string is attached to the number of experiments per plane, these are exchanged sequentially with steped probability, and then changed to real values.

A suitable method for such optimization problems is the application of combinatorial and evolutionary methods (Ugi, I. et al., Chimia 51 (1997) 39 - 44). These algorithms have been employed in the past in biochemistry and active ingredient research in order to select within a time as short as possible new substances with a desired specific activity from a plurality of compounds. These principles have also been used in

the meantime in the development of homogenous catalysts (DE-A 197319904). In the aforementioned applications the substances to be examined are always in solution. The activity range of the desired property (e.g., catalytic activity and selectivity) 5 is limited to a molecule whose optimal element composition and structure is to be found.

In contrast to this, in the heterogeneous catalysis the object is to select the catalytically most effective inorganic solid materials and to determine their optimal weight 10 proportion in the final catalyst. By application of new strategies in the development of heterogeneous catalysts, the experimental expenditure in the catalyst development is to be reduced, on the one hand, and the probability of finding an optimal catalyst is to be increased, on the other hand, in comparison to the currently still substantially empirically 15 oriented methods employed in practice.

The combinatorial approach is an effective developmental strategy when a large number of parameters affect the properties of products. Despite the great success of this 20 strategy in the development of new medicaments, the application of combinatorial methods in the inorganic chemistry and catalysis is a new field. The first application of combinatorial methods in the development of new solid materials was reported in the year 1995 by Schultz et al., Science, 268 25 (1995) 1738 and Science 270 (1995) 273. The authors have demonstrated that the solid material libraries can be tested with respect to superconductivity and magneto resistance. In the same year, libraries of complexes for the selective bonding 30 of metal ions as well as of phosphine-containing peptide ligands for the Rh(I)-catalyzed hydrogenation of methyl-2-acetamido acrylate to N-acetyl alanine methyl ether were established.

The synthesis of libraries containing a large number (up to 26,000) of combinations of inorganic materials on a silicon 35 matrix has been described (E. Danielson et al., Nature 389 (1997) 944). This technology was tested, inter alia, on the example of heterogeneous catalytic CO oxidation for determining analytically active solid materials. The obtained results were represented in three-dimensional diagrams from which the

combinations which resulted in high CO<sub>2</sub> yields and thus an increased catalytic activity could be determined.

Moreover, a synthesis of a library of polyoxy metallates with Keggin structure have been described (C.L. Hill et al., J. Mol. Catal. A 114 (1996) 114); 39 homogeneously dissolved catalysts were prepared by mixing aqueous solutions of Na<sub>2</sub>MO<sub>4</sub>·2H<sub>2</sub>O, NaVO<sub>3</sub> und Na<sub>2</sub>MPO<sub>4</sub> (M = W, Mo). The resulting solutions were used without further treatments in the aerobic oxidation of tetrahydro thiophen to sulfoxide at 95°. The educt conversion and the product formation were determined by means of the GLC analysis and presented as a three-dimensional reaction histogram (x-axis - Mo/W content; y axis - V content; z axis - product yield). Since with most catalysts comparable results were obtained, no sound conclusion could be drawn.

A combinatorial strategy has been used by Mallouk et al. (Fuel Cell Seminar: Orlando, Florida (1996) 686) in the development and optimization of alloys of three metals which are used as anode materials in the electrochemical oxidation of methanol. For the preparation of libraries (9 arrays with 135 compositions) five noble metals (Pt, Ru, Os, Rh, and Pd) were used. This work is an example for an effective parallel testing.

Combinatorial libraries of metal catalysts supported on Al<sub>2</sub>O<sub>3</sub> (inter alia Bi, Cr, Co, Cu, Ni, Pd) with 16 elements of a matrix are used by Willson et al. in the hydrogen oxidation reaction. The reactor was furnished with a special camera for the in-situ IR thermography; the catalytic activity was therefore determined via the ignition temperature. A disadvantage of the analytical method employed in this work is that the information in regard to product selectivity is missing.

In the above described methods of a combinatorial approach and their use for determining active compounds and optimized catalysts, very many syntheses for these target materials are performed which are time-consuming and material-intensive.

It is therefore an object of the invention to develop a method for preparing heterogeneous solid catalysts for a

predetermined reaction with reduced expenditure wherein the combinatorial approaches are supplemented or replaced by other optimization methods.

According to the invention evolutionary principles such as crossing and mutation are used and, in this connection, a stochastic modification of the catalyst composition is employed. These methods do not lead to a pure random search but, by an activity and selectivity determined selection of the catalysts to be modified, to a directed optimization which focuses quickly and parallel on several promising areas of the catalysts composition.

According to the invention the following procedure is followed:

- (i) preparing substance libraries of individual catalytic materials and their mixtures,
- (ii) testing of materials, i.e., individual materials and their mixtures of these substance libraries, with regard to their catalytic activity,
- (iii) determining the chemical structure of the catalytically active materials,
- (iv) carrying out an iterative repetition of the steps (i) to (iii) or also (iv), based on the results obtained according to (ii) and (iii), with the goal of catalyst optimization.

This procedure can be realized or practically applied in the development of heterogeneous catalysts as follows:

In the first step (i) primary components (individual materials or catalytically active phases), which have already been described or are known or have been determined empirically or intuitively for the individual reactions steps of the heterogeneous catalytic reaction under consideration, are selected and introduced into the substance library; wherein by a random selection arbitrary mixtures of these individual materials are produced. In the second step (ii) these materials finally determined and prepared in this way (first generation of catalysts) are catalytically tested (for example, activity, selectivity, space-time yield); these two procedures, i.e., preparation and testing, are performed parallel as much as possible, respectively. The successful materials with respect to catalysts optimization of the step (ii) are physically and

physical-chemically characterized in particular with respect to their reproducible preparation in step (iii) and present the foundation for the subsequent second generation of catalysts. This second generation is generated according to methods of 5 biological evolution from the successful materials of the first generation and then subjected to the steps (ii) and (iii).

Methods of biological evolution in this context are to be understood as crossing and mutation. In this connection, by means of stochastic methods, such as a random-check generators, 10 throwing dice, drawing, a change of catalyst components and/or weight proportions of one or more catalysts of a selected pool of catalysts of the previous generation is performed by an arbitrary and/or random new structuring.

In the second and the subsequent iterations, the most 15 successful catalysts of all generations are employed as a foundation, respectively, whose total number relative to the total number of catalysts of a generation, however, is generally small. In general, it will be 1 to 50 % of the catalysts of one generation.

The described iterations are performed until no improvement of the catalytic behavior of the materials with respect to activity and/or selectivity for the reaction under consideration can be determined anymore.

The method for selecting components for the preparation 25 of active and/or selective solid catalysts of inorganic or organometallic materials or mixtures thereof is comprised advantageously of the following steps, in which

(a) for a catalytic reaction a number  $n_1$  of solid catalysts of the elements of the periodic table of the elements 30 (PTE) in the form of compounds of the formula (I)

$$(A_{a_1}^1 \dots A_{a_i}^i) - (B_{b_1}^1 \dots B_{b_j}^j) - (D_{d_1}^1 \dots D_{d_k}^k) - (T_{t_1}^1 \dots T_{t_l}^l) - O_p \quad (I)$$

are prepared, wherein  $A^1 \dots A^i$  are  $i$  different main components which are selected from the elements of the PTE, except trans uranium and noble gas elements, preferably of the group

35 Mg, Ca, Sr, Ba, Y, La, Ti, Zr, V, Nb, Cr, Mn, Tc, Re, Fe, Ru, Os, Co, Rh, Ir, Ni, Pd, Pt, Cu, Ag, Au, Zn, Cd, Hg, B, Al, Ga, In, C, Si, Sn, Pb, N, P, As, Sb, Bi, S, Se, Te, F, Cl, Ce and Nd and the number  $i$  is between 1 and 10,

B<sup>1</sup> .. B<sup>j</sup> are j different minor components selected from the group of the elements

Li, Na, Ka, Mg, Ca, Sr, Ba, Y, La, Ti, Zr, V, Nb, Cr, Mn, Tc, Re, Fe, Ru, Os, Co, Rh, Ir, Ni, Pd, Pt, Cu, Ag, Au, Zn, Cd, Hg,

5 B, Al, Ga, In, C, Si, Sn, Pb, N, P, As, Sb, Bi, S, Se, Te, F, Cl, Ce and Nd and the number j is between 1 and 10,

D<sup>1</sup> .. D<sup>k</sup> are k different doping elements which are selected from the group of the elements

Li, Na, Ka, Mg, Ca, Sr, Ba, Y, La, Ti, Zr, V, Nb, Cr, Mn, Tc,

10 Re, Fe, Ru, Os, Co, Rh, Ir, Ni, Pd, Pt, Cu, Ag, Au, Zn, Cd, Hg, B, Al, Ga, In, Si, Sn, Pb, N, P, As, Sb, Bi, S, Se, Te, F, Cl, Ce and Nd and the number k is between 1 and 10,

15 T<sup>1</sup> .. T<sup>l</sup> are l different support components which are comprised of oxides, carbonates, carbides, nitrides, borides of the elements Mg, Ca, Sr, Ba, La, Zr, Ce, Al, Si or a mixed phase of two or more thereof, and the number l is between 1 and 10, and O is oxygen,

20 a<sub>1</sub>..a<sub>i</sub> are identical or different mole fractions of 0 to 100 mole-% with the provision that the mole fractions a<sub>1</sub>..a<sub>i</sub> cannot all at the same time be 0,

b<sub>1</sub> .. b<sub>j</sub> are mole fractions of 0 to 90 mole-%, preferably 0 to 50 mole-%,

d<sub>1</sub> .. d<sub>k</sub> are mole fractions of 0 to 10 mole-%,

t<sub>1</sub> .. t<sub>l</sub> are mole fractions of 0 bis 99.99 mole-%,

25 p is a mole fraction of 0 to 75 mole-%, wherein the sum of all mole fractions a<sub>i</sub> + b<sub>j</sub> + d<sub>k</sub> + t<sub>l</sub> may be not greater than 100 %, and

30 the number n<sub>1</sub> of catalysts with different quantitate composition and/or different chemical composition is in the range of 5 to 100,000, preferably in the range of 5 to 100;

(b) the activity and/or selectivity of the n<sub>1</sub> solid catalysts prepared according to (a) of the first generation is determined experimentally for a catalytic reaction in a reactor or in several reactors switched parallel;

35 (c) a number of 1 - 50 % is selected as number n<sub>2</sub> from the number n<sub>1</sub> of the catalysts of the first generation having the highest activities for a specific reaction and/or highest selectivities for the desired product or product mixture of the catalytic reaction;

are exchanged between two catalysts selected from the number  $n_3$  with a probability of  $W_{cat} = \frac{1}{n_3} \cdot 100\%$  and/or that the amount

of mass  $a_1 \dots a_i, b_1 \dots b_j, d_1 \dots d_k$  and  $t_1 \dots t_l$  of the catalyst components  $A^1 \dots A^i, B^1 \dots B^j, D^1 \dots D^k$  and  $T^1 \dots T^l$

5 for some of the catalysts selected with a probability of  $W_{cat} = \frac{1}{n_3} \cdot 100\%$  are varied in that new values for the mole

fractions  $a_1 \dots a_i, b_1 \dots b_j, d_1 \dots d_k$  and  $t_1 \dots t_l$  are determined within the limits defined under (a);

10 in this way new catalysts of the general formula (I) with the meaning of  $A^1 \dots A^i, B^1 \dots B^j, D^1 \dots D^k, T^1 \dots T^l, a_1 \dots a_i, b_1 \dots b_j, d_1 \dots d_k$  and  $t_1 \dots t_l$  and  $p$  defined under (a) are produced in a number  $y_3$  which form the catalysts of the third generation;

(h) the activity and/or selectivity is of the  $y_3$  new solid catalysts of the third generation prepared according to

15 (g) is determined experimentally for the same specific reaction as in (b) in one or more reactors;

20 (i) a number of  $n_{n+1}$  solid catalysts of the  $n$ -th generation, having the highest activities for a catalytic conversion and/or the highest selectivities for the desired product and product mixture of all solid catalysts of the first to  $n$ -th generation, is selected, wherein the number  $n_{n+1}$  is 1 to 50 % of the number  $n_1$ ;

25 (j) the catalyst components contained in the number  $n_{n+1}$  of the catalysts with a pre-set probability  $W$ , which results for each of the components  $A^1 \dots A^i, B^1 \dots B^j, D^1 \dots D^k$  and  $T^1 \dots T^l$  from the corresponding equations

$$W_A = \frac{1}{i \cdot n_{n+1}} \cdot 100\%, W_B = \frac{1}{j \cdot n_{n+1}} \cdot 100\%, W_D = \frac{1}{k \cdot n_{n+1}} \cdot 100\%, W_T = \frac{1}{l \cdot n_{n+1}} \cdot 100\%$$

are exchanged between two catalysts selected from the number

30  $n_{n+1}$  with a probability of  $W_{cat} = \frac{1}{n_{n+1}} \cdot 100\%$  and/or that the

amount of mass  $a_1 \dots a_i, b_1 \dots b_j, d_1 \dots d_k$  and  $t_1 \dots t_l$  of the catalyst components  $A^1 \dots A^i, B^1 \dots B^j, D^1 \dots D^k$  and  $T^1 \dots T^l$  for some of the catalysts selected with a probability of

$W_{cat} = \frac{1}{n_{n+1}} \cdot 100\%$  are varied in that new values for the mole

fractions  $a_1 \dots a_i, b_1 \dots b_j, d_1 \dots d_k$  and  $t_1 \dots t_l$  are determined within the limits defined under (a);

in this way new catalysts of the general formula (I) with the meaning of  $A^1 \dots A^i, B^1 \dots B^j, D^1 \dots D^k, T^1 \dots T^l, a_1 \dots a_i,$

5  $b_1 \dots b_j, d_1 \dots d_k$  and  $t_1 \dots t_l$  and  $p$  defined under (a) are produced in a number  $y_{n+1}$  which form the catalysts of the  $(n+1)$ -th generation;

(k) the activity and/or selectivity is of the  $y_{n+1}$  solid catalysts of the  $(n+1)$ -th generation prepared according to

10 (g) is determined experimentally for the same specific reaction as in (b) in one or more reactors;

(l) the selection according to the steps (c) + (f) +  
15 (i), the preparation of a new catalyst generation according to the steps (d), (g), (j), and the activity/selectivity determination according to the steps (e) + (h) + (k) is continued up to obtaining a catalyst generation in which the activity and/or selectivity relative to the previous generations as an arithmetic mean is not increased or no longer significantly increased ( $>1\%$ ).

20 The selection number  $n_2, n_3, \text{ or } n_{n+1}$  corresponds preferably to 5 to 30 % of the number  $n_1$ .

The exchange of the catalysts for the variation of the amount of mass or exchange and variation in the steps (d),  
25 (g), and (j) is performed preferably by means of a numerical random-check generator. In this connection, advantageously the program codes G05CAF, G05DYF, G05DZF oder G05CCF of the NAG Library (NAG FORTRAN Workstation Library, NAG Group Ltd., 1986) of a numerical random-check generator are used.

However, it is also possible to employ random-check  
30 generators which are available freely on the Internet or which are commercially available as software such as "Numerical Recipes in FORTRAN, PASCAL oder C", Cambridge University Press, or IMSL Libraries of the FORTRAN compilers DIGITAL visual Fortran Professional Edition.

35 Other stochastic methods such as rolling the dice or drawings can also be used for this step.

When employing such methods, in the step (d) several catalyst components can be selected and their corresponding mole fractions can be exchanged between the previously selected

catalyst components (crossing). Accordingly, it is also possible to effect via the molar fractions, which are changed from a finite value to zero or from zero to a finite value, an exchange of the individual catalyst components themselves by  
5 means of crossing so that overall a new composition of the catalyst of the new generation is obtained. However, it is also possible to reduce or enlarge (mutation) the catalyst components selected, for example, by means of random-check generator, by multiplication with factors which are determined  
10 randomly or freely selectable from the set of real numbers between 0 and 10,000 so that the new catalyst of the next catalyst generation contains the same components but in different concentrations so that also the ratios of the components relative to one another can be changed.

15 In the method step (a) the number  $n_1$  of catalysts having different weight composition and/or different chemical composition is in the range of 5 to 100.

Advantageously, the preparation of the catalyst mixtures is carried out by mixing salt solutions of the elements of the component  $A^1 \dots A^i, B^1 \dots B^j, D^1 \dots D^k$  and  $T^1 \dots T^l$  and a subsequent thermal treatment in the presence of a reactive or inert gas phase (in the following referred to as tempering) or by common precipitation of sparingly soluble compounds and subsequent tempering or by loading the support components  $T^1 \dots$   
20  $T^l$  with salt solutions or gaseous compounds of the components  $A^1 \dots A^i, B^1 \dots B^j, D^1 \dots D^k$  and subsequent tempering, wherein the employed salts may be nitrates, sulfates, phosphates, carbonates, halogenides, oxalates, carboxylates or mixtures thereof or carbonyl compounds or acetyl acetonates.

25 The preparation of new catalyst mixtures of the second to  $n$ -th generation can be realized by mechanically mixing the prepared solid catalyst of the respective previous generations. Further advantageous embodiments reside in that the catalytic reaction is performed with liquid, vaporized, or gaseous reactants and that the reactants for the catalytic reaction are supplied to several reactors, and the product stream exiting  
30 from the reactors is analyzed separately for each individual reactor.

(d) the catalyst components contained in the number  $n_2$  of the catalysts with a pre-set probability  $W$ , which results for each of the components  $A^1 \dots A^i, B^1 \dots B^j, D^1 \dots D^k$  and  $T^1 \dots T^l$  from the corresponding equations

5       $W_A = \frac{1}{i \cdot n_2} \cdot 100\%, W_B = \frac{1}{j \cdot n_2} \cdot 100\%, W_D = \frac{1}{k \cdot n_2} \cdot 100\%, W_T = \frac{1}{l \cdot n_2} \cdot 100\%$

are exchanged between two catalysts selected from the number  $n_2$  with a probability of  $W_{cat} = \frac{1}{n_2} \cdot 100\%$  and/or that the amount

of mass  $a_1 \dots a_i, b_1 \dots b_j, d_1 \dots d_k$  and  $t_1 \dots t_l$  of the catalyst components  $A^1 \dots A^i, B^1 \dots B^j, D^1 \dots D^k$  and  $T^1 \dots T^l$

10     for some of the catalysts selected with a probability of  $W_{cat} = \frac{1}{n_2} \cdot 100\%$  are varied in that new values for the mole

fractions  $a_1 \dots a_i, b_1 \dots b_j, d_1 \dots d_k$  and  $t_1 \dots t_l$  are determined within the limits defined under (a);

15     in this way new catalysts of the general formula (I) with the meaning of  $A^1 \dots A^i, B^1 \dots B^j, D^1 \dots D^k, T^1 \dots T^l, a_1 \dots a_i, b_1 \dots b_j, d_1 \dots d_k$  and  $t_1 \dots t_l$  and  $p$  defined under (a) are produced in a number  $y_2$  which form the catalysts of the second generation;

20     (e) the activities and/or selectivities of the  $y_2$  solid catalysts of the second generation are determined experimentally for the same specific reaction as in (b) in one or more reactors;

25     (f) a number of the  $n_3$  catalysts of the second generation, having the highest activities for a specific reaction and/or highest selectivities for the desired product and product mixture of all solid catalysts of the first and second generation, is selected, wherein the number  $n_3$  is 1 to 50 % of the number  $n_1$ ;

30     (g) the catalyst components contained in the number  $n_3$  of the catalysts with a pre-set probability  $W$ , which results for each of the components  $A^1 \dots A^i, B^1 \dots B^j, D^1 \dots D^k$  and  $T^1 \dots T^l$  from the corresponding equations

$$W_A = \frac{1}{i \cdot n_3} \cdot 100\%, W_B = \frac{1}{j \cdot n_3} \cdot 100\%, W_D = \frac{1}{k \cdot n_3} \cdot 100\%, W_T = \frac{1}{l \cdot n_3} \cdot 100\%$$

For performing the catalytic reaction, preferably 5 to 1,000 reactors, comprised of spaces with catalytically active material arranged therein, are switched parallel to one another or arranged in arrays, wherein the diameter of the spaces is 5 100  $\mu\text{m}$  to 10 mm and the lengths are 1 mm to 100 mm. The throughput of the reactants is selected for a predetermined reactor length such that the desired conversion rate is achieved.

The reactor can be realized by a monolithic block with 10 many parallel channels, wherein the channels can be closed the inlet or outlet side individually or in a larger number also during the catalytic reaction, or by a porous module, preferably with channels extending parallel to the flow direction of the reaction mixture, which channels can be closed 15 selectively at the inlet or outlet side individually or in a larger number also during the catalytic reaction.

Advantageously, the reactants are supplied for the catalytic reaction to the above reactors and the composition of the product streams exiting the reactors are analyzed by a measuring sensor wherein the measuring sensor is guided two-dimensionally across the outlet cross-sections of all reactors 20 or the reactors are moved two-dimensionally relative to the measuring sensor and the portion of the product streams received by the measuring sensor is supplied to the analytical device. The analytical device can be a gaschromatograph, a mass 25 spectrometer, or another device for the analysis of gas or liquid mixtures.

The reaction mixture can have added thereto suitable indicators which indicate the presence of individual or several 30 educts or products and thus make possible their analysis in the reactant mixture. The preparation of the solid catalysts can be realized from solids, solutions, or dispersions.

The term "catalyst improved in regard to activity or selectivity" means that the catalysts with respect to their 35 activity or selectivity or with respect to both properties shows improved values. This compares to the improvement of the space/time yield.

The term «stochastic method» includes all not strictly deterministic processes with a random component. The stochastic methods of the invention are finite or discrete methods.

5 The invention will be explained with the aid of the attached drawing. It is shown in:

Fig. 1 a diagram showing the change of yield of the respectively best five catalysts during the first three generations of catalyst optimization according to example 1;

10 Fig. 2 a diagram as in Fig. 1 according to example 2.

15 The invention will be explained with the following examples. Example 1 concerns the search for an optimized catalyst for the partial oxidation of propane to its oxygen derivatives which encompasses the sum of acrolein, acetic acid, and acrylic acid.

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**Example 1**

### Example 1

20 The selection and mixture of individual catalyst components which are divided into main, minor, doping, and support components as well as the testing and further improvement of the catalyst mixtures with application of evolutionary optimization strategies is demonstrated.

25 First 30 catalysts (phase I), subsequently 10 catalysts (phase II), and then further 10 catalysts (phase III), comprised of main components, minor components, doping components, and support material are prepared with the goal of convert propane to its oxygen derivatives by oxidation with oxygen and to minimize the resulting oxides CO and CO<sub>2</sub> (compare step (a) above). The course of the process comprises the following steps and leads to the respective denoted results.

30 1. Catalyst Generation

Step 1. The main components are selected from the oxides of the elements V, Mo, Nb, Bi, P. The proportion of the main components are varied between 0 and 50 mole-%. The minor components are selected from the oxides of the elements Mn, Sb, Sn, and B. The proportions of the minor components are varied between 0 and 50 mole-%. The doping components are selected from the oxides of the elements Cs and either Fe or Co, either Ag or Cu, and either Ga or In. The proportions of the doping components are varied between 0 and 5 mole-%. As a further

doping component Pd was used which was either not introduced or introduced in an amount of  $10^{-4}$  mole-%. As a support component Al<sub>2</sub>O<sub>3</sub> was provided which was either not present or present in an amount of 50 % by weight in the catalyst.

5       The sum of all weight or mole ratios of the main, minor, and doping and support components yields always 100 %.

Step 2. The catalysts which were used for testing, were obtained according to the following manufacturing process. Compounds (oxides, oxalates, or nitrates) of the elements 10 mentioned in step 1 were dissolved in a little water or suspended, mixed with one another, and the mixture was evaporated. The resulting solid material was dried for 1 hr. at 200 °C and 3 hrs. at 400 °C, subsequently ground intensively for 1 hr. in a ball mill and tempered for 3 hrs. at 600 °C in air.

15       Step 3. The catalysts compositions of the first generation obtained by the random-checked generators G05DZF, G05CAF, G05DYF und G05CCF of the NAG-Bibliothek (NAG FORTRAN Workstation Library, NAG Group Ltd., 1986) are compiled in 20 Table 1.

Step 4. The testing of the catalysts is carried out parallel in six quartz reactors (inner diameter 6 mm) which are introduced into the heatable and coolable fluidized sand bed for temperature control. Alternative configurations of the parallel 25 testing of the solid catalysts are possible according to the above description.

The following standard conditions were selected for the testing of the catalysts: T = 500 °C, m<sub>catalyst</sub> = 1,0 g, V<sub>total</sub> per reactor = 28 mlSTP min<sup>-1</sup> mit V<sub>C3H8</sub> = 0.8 mlSTP min<sup>-1</sup>, V<sub>O2</sub> = 30 5.6 mlSTP min<sup>-1</sup>, V<sub>H2O</sub> = 12,0 mlSTPmin<sup>-1</sup>, V<sub>Ar</sub> = 21,6 mlSTP min<sup>-1</sup>.

The catalysts were used for the reaction and tested with respect to the sum of the yields of acrolein and acrylic acid obtained under the standard experimental conditions (compare 35 step (b) above; corresponds also to this step in claim 2). The concentration of propane, propene, ethylene, the resulting oxygen derivatives as well as of CO and CO<sub>2</sub> was analyzed by means of a gaschromatograph and mass spectrometer.

Step 5. The results of the test of the first generation of catalysts are compiled in the form of the sum of the yield of acrolein and acrylic acid in Table 1. Significant differences in the yields of the 30 tested catalysts result. The best 5 five catalysts (Nos. 4, 13, 17, 19, 21) all contain, with the exception of No. 13, the support component. Moreover, among these best catalysts, Mo as a main components as well as Sn as an minor component are present frequently. With the exception of Fe as a doping component, however, all employed 10 catalyst components are still represented in the best five catalysts of the first generation.

## 2. Catalyst generation

Step 6. The second generation of catalysts was obtained in that first the five catalysts Nos. 4, 19, 21, 13, and 17 with the highest oxygenate yield of the 30 (corresponding to 17 % of the first generation of catalysts) that were previously tested were selected (compare step (c) above).

Step 7. The compositions of 10 new catalysts of the second generation were obtained in that

a) of the main, minor, doping, and support components of the five best catalysts (Table 1: Nos. 4, 19, 21, 13 and 17) six new combinations of main, minor, doping, and support components are formed (compare step (d) above), in that, for example, for the composition of the catalyst No. 1 of the second generation (Table 2) first the catalyst No. 17 (in the following catalyst No. \_ = K.) was selected by means of ZG1-Best5 [by means of the numerical random-check generators G05DYF, G05DZF, G05CCF of the NAG Library (NAG FORTRAN Workstation Library, NAG Group Ltd., 1986) of the best five catalysts] and subsequently by means of ZG1 [by means of the numerical random-check generators G05DYF, G05DZF, G05CCF of the NAG Library (NAG FORTRAN Workstation Library, NAG Group Ltd., 1986)] the main component Bi of K.17. Subsequently, K.21 (Table 1) was selected by means of ZG1-Best5 and then by means of ZG1 the main component P of K.21. Subsequently, K.4 (table 1) was selected by ZG1-Best 5 and then by means of ZG1 the minor component Sn of K.4. Subsequently, K.21 was selected by means of ZG1-Best5 and then by means of ZG1 the auxiliary component B of K.21. Subsequently, K.14 (Table 1)

was selected by means ZG1-Best5 and then by means of ZG1 the trace component Fe of K.14. Subsequently, K.19 (Table 1) was selected by means of ZG1-Best5 and then by means of ZG1 the trace component Co of K.19. Subsequently, K.17 (Table 1) was  
5 selected by ZG1-Best5 and then by means of ZG1 the trace and doping components Cs and Pd of K.17. The thus selected components were combined with the original molar amounts to a new catalysts composition. In analogy, K.2, 3, 6, 7, 8 of the second catalyst generation (Table 2) were obtained.

10 b) The molar components of the main, minor, and doping components of the two best catalyst with the highest oxygenate yield (Table 1, Nos. 4 and 19) according to the above step (d) are changed in that the components Mo, Nb, Sb, Sn, Co and Ga of K.4 of the first generation are selected by means of ZG1 and the molar fractions of the selected components are stochastically changed by means of ZG2 [by means of the numerical random-check generators G05CAF, G05DZF, G05CCF of the NAG Library (NAG FORTRAN Workstation Library, NAG Group Ltd., 1986)]. Subsequently, the components Mo, Bi, P, Sn, Co of K.19 of the first generation were selected by ZG1 and the molar fractions of the selected components were stochastically changed by means of ZG2.  
15  
20 K.4 and K.5 of the second generation were obtained (Table 2). In analogy, K.9 and K.10 of the second generation were obtained. The preparation of the resulting total of 10 new catalysts of the second generation is carried out in analogy to that of the first generation (step 2).

25 Step 8. With the process described in step 7, 10 new catalyst compositions were determined, prepared according to the procedure (compare step 1), and then tested parallel under standard conditions as described in step 4 (compare above step (e)). The results are compiled in Table 2. These new catalysts contain frequently Mo as a main component and Sn as a minor component. Also, P as a main component and Co as a  
30 doping component, which already occurred with greater frequency in the best catalysts of the first generation, are also frequently contained in the new catalysts of the second generation.

Third catalyst generation

Step 9. From the quantity of the first and second catalyst generation the five catalysts were selected again which had the highest yield of oxygen derivatives (compare above step (f)). These are the catalysts of Table 1: Nos. 4, 19, 21 and 5 of Table 2: Nos. 2, 3. With the 10 new catalysts of the second generation initially no higher yields than with the best catalysts of the first generation are obtained. However, the catalysts Nos. 2 and 3 of the second generation displace the catalysts Nos. 19 and 21 from the third and fourth rank 10 (see also Fig. 1).

Step 10. The composition of the 10 new catalysts to be produced of the third generation was obtained in that with the five catalysts selected in step 9 the same procedure as in step 7 was performed (see Table 3, compare above step (g)). Accordingly, K.4 (Table 2) was selected with ZG1-Best5 and then by means of ZG1 the main component Nb of K.4 (Table 2). Subsequently, K.21 (Table 1) was selected by means of ZG1-Best5 and then by means of ZG1 the main component P of K.21 (Table 1). Subsequently, K.3 (Table 2) was selected by means of ZG1-Best5 and then by means of ZG1 the trace component Fe of K.14. Subsequently, K.19 (Table 1) was selected by means of ZG1-Best5 and then by means of ZG1 the doping component Co of K.3 (Table 2). Subsequently, K.4 (Table 1) was selected by means of ZG1-Best5 and then by 25 means of ZG1 the doping component Ga of K.4. Subsequently, K.2 (Table 2) was selected by means of ZG1-Best5 then by means of ZG1 the support component of K.2 (Table 2). The thus selected components were combined with their original molar fractions to a new catalyst composition. After the 30 combination, the molar fraction of the main component Nb was stochastically changed by means of ZG3 [by means of the numerical random-check generators G05CAF and G05CCF of the NAG Library (NAG FORTRAN Workstation Library, NAG Group Ltd., 1986)]. In analogy, K.2, 3, 6, 7, and 8 of the third catalyst 35 generation (Table 3) were obtained.

b) The same procedure as in portion b) of step 7 was carried out.

K.4 and K.5 of the third generation were obtained (Table 3). In analogy, K.9 and 10 of the third generation were obtained.

The preparation of the resulting total of 10 new catalysts of the third generation was carried out as in the first and second generation (steps 2 and 7).

Step 11. The 10 new catalysts of the third catalyst generation were prepared according to procedure (compare step 1) and tested parallel under standard conditions as in step 4 (compare above step (h)). Among these 10 new catalysts there are now two (Nos. 4 and 9) with which the previously highest yields are surpassed. Accordingly, the catalysts Nos. 4 and

19 (Table 1) are displaced from the first and second rank (compare Fig. 1).

Step 12. The selection of catalyst compositions of the following generations (the n-th generation) was carried out in analogy to the steps 6 - 8, respectively, 9 - 11 in that, respectively, the five best catalysts of all already tested catalyst generations were selected and used for the determination of the composition of the 10 new catalysts of the n-th catalyst generation (compare above steps (i), (j), (k)).

Result:

When the compositions of the five best catalysts of the first through third catalyst generation are compared, it is apparent that all catalysts contain Mo, Sn, Co, and the support component. The qualitative compositions of the three best catalysts are near identical. These catalysts contain all Mo, Nb, Sb, Sn, Co, Ga and the support component. The two best catalysts contain, in addition, also the doping components Cu and Pd. This underscores that the catalyst compositions with increasing generation number approximate one another, i.e., disruptive components are no longer considered during the course of optimization and the components of the catalysts with high oxygenate yield are more strongly taken into consideration upon determination of new catalysts compositions. On the basis of this evolutionary strategy, already in the third catalyst generation a 100 % higher oxygenate yield than in the first generation is obtained (Fig. 1).

Example 2

First, 20 catalysts (generation I), subsequently 10 catalysts (generations II and III), and subsequently further 10 catalysts (generation IV), based on 13 oxides which serve as primary catalyst components, are prepared and tested in  
5 the oxydative dehydrogenation of propane. The goal was to prepare propene from propane with a yield as high as possible and selectivity as high as possible by oxydative dehydrogenation. The course of the process comprised the following steps and resulted in the respectively denoted  
10 results.

1. Catalyst generation

Step 1. The components were selected from the oxides of the elements V, Mo, Mn, Fe, Zn, Ga, Ge, Nb, W, Co, Ni, Cd, In. The atom parts of the individual elements in the catalyst were varied between 0 and 1. Each catalyst contains three of the elements V, Mo, Mn, Fe, Zn, Ga, Ge, Nb, W, Co, Ni, Cd, In. The sum of all atom parts of these elements always results in 1.

Step 2. The catalyst compositions of the first generation are compiled in Table 4 which were obtained by means of ZG4 [numerical random-check generators G05DZF, G05CAF, G05DYF, G05CCF of the NAG Library (NAG FORTRAN Workstation Library, NAG Group Ltd., 1986)].

Step 3. The catalysts which were used for testing were obtained by the following manufacturing process:

Compounds ( $\text{NH}_4\text{VO}_3$ ,  $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ ,  $\text{Mn}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ ,  $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ ,  $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ ,  $\text{Ga}_2\text{O}_3$ ,  $\text{GeO}_2$ ,  $\text{Nb}_2\text{O}_5$ ,  $\text{H}_2\text{WO}_4$ ,  $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ ,  $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ ,  $\text{Cd}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ ,  $\text{In}(\text{NO}_3)_3 \cdot \text{H}_2\text{O}$ ) of the elements named in step 1 were dissolved in water or suspended, mixed with one another, and the mixture evaporated. The resulting solid material was dried for 10 hrs. at 120 °C. and subsequently calcinated for 3 hrs. at 600 °C in air.

Table 4. Composition of Catalysts of the First Generation

| Cat. No. | Composition  | Cat. No. | Composition  |
|----------|--|----------|--|
| 1/1      | $\text{Fe}_{0.79}\text{Ga}_{0.02}\text{Nb}_{0.19}\text{O}_x$ | 1/11     | $\text{V}_{0.47}\text{W}_{0.19}\text{Ni}_{0.33}\text{O}_x$   |
| 1/2      | $\text{Mo}_{0.44}\text{Ni}_{0.23}\text{In}_{0.33}\text{O}_x$ | 1/12     | $\text{Mn}_{0.41}\text{Ga}_{0.51}\text{Nb}_{0.08}\text{O}_x$ |

|      |                                  |      |                            |
|------|----------------------------------|------|----------------------------|
| 1/3  | $Zn_0.70Ge_0.08Co_0.22O_x$       | 1/13 | $Mo_0.45Co_0.22In_0.33O_x$ |
| 1/4  | $V_0.33Fe_0.43Cd_0.24O_x$        | 1/14 | $Fe_0.75Ge_0.05W_0.20O_x$  |
| 1/5  | $Ga_0.01Nb_0.33Ni_0.66O_x$       | 1/15 | $V_0.33Mn_0.43Ni_0.23O_x$  |
| 1/6  | $Mo_0.33Zn_0.42In_0.25O_x$       | 1/16 | $Zn_0.67Nb_0.1Co_0.23O_x$  |
| 1/7  | $Ge_0.11W_0.33Cd_0.56O_x$        | 1/17 | $Mo_0.33Fe_0.42Cd_0.25O_x$ |
| 1/8  | $V_0.26Mn_0.33Ga_0.41O_x$        | 1/18 | $Ga_0.01W_0.33Ni_0.66O_x$  |
| 1/9  | $Nb_0.16Co_0.33$<br>$In_0.51O_x$ | 1/19 | $Mn_0.33Zn_0.41In_0.25O_x$ |
| 1/10 | $Mo_0.42Ge_0.44Fe_0.53O_x$       | 1/20 | $Ge_0.14Co_0.33Cd_0.53O_x$ |

Step 4. The testing of the catalysts was carried out parallel in six quartz reactors (inner diameter 6 mm) which were introduced into a heatable and coolable fluidized sand bed for 5 temperature control. The following standard experimental conditions were selected for the testing of the catalysts: T = 500 °C,  $m_{catalyst}$  = 0.3 g,  $C_3H_8/O_2/N_2$  = 2/1/2, Vtotal per reactor = was varied between 10 and 100 ml/min.(STP). The catalysts were used for the reaction and tested with respect to 10 the propane conversion and propene selectivity under the aforementioned experimental conditions (compare step (b) above). The concentration of propane, propene, ethylene, methane, and the resulting oxygen derivatives as well as of CO and CO<sub>2</sub> was analyzed by means of a gaschromatograph.

Step 5. The results of the tests of the first generation of catalysts (propane conversion, propene selectivity, and propene yield) are represented in Table 5. Among the 20 tested catalyst significant differences in the yields resulted which are a product of conversion and selectivity. For catalysts (No. 1/4, 1/8, 1/10, 1/15) show the best results for the catalytic 15 conversion.

20

Table 5. Catalytic Results of the First Generation

| Cat.-<br>No. | Composition  | X( $C_3H_8$ )<br>% | S( $C_3H_6$ )<br>% | Y( $C_3H_6$ )<br>% |
|--------------|--|--------------------|--------------------|--------------------|
| 1/1          | Fe <sub>0.79</sub> Ga <sub>0.02</sub> Nb <sub>0.19</sub> | 10.7               | 17.7               | 1.9                |
| 1/2          | Mo <sub>0.44</sub> Ni <sub>0.23</sub> In <sub>0.33</sub> | 11.8               | 14.3               | 1.7                |
| 1/3          | Zn <sub>0.70</sub> Ge <sub>0.08</sub> Co <sub>0.22</sub> | 20.3               | 0.04               | 0.01               |
| 1/4          | V <sub>0.33</sub> Fe <sub>0.43</sub> Cd <sub>0.24</sub>  | 15.3               | 24.5               | 3.7                |
| 1/5          | Ga <sub>0.01</sub> Nb <sub>0.33</sub> Ni <sub>0.66</sub> | 8.9                | 2.5                | 0.2                |
| 1/6          | Mo <sub>0.33</sub> Zn <sub>0.42</sub> In <sub>0.25</sub> | 1.3                | 26.2               | 0.3                |
| 1/7          | Ge <sub>0.11</sub> W <sub>0.33</sub> Cd <sub>0.56</sub>  | 0.2                | 15.6               | 0.03               |
| 1/8          | V <sub>0.26</sub> Mn <sub>0.33</sub> Ga <sub>0.41</sub>  | 6.9                | 43.4               | 3.0                |
| 1/9          | Nb <sub>0.16</sub> Co <sub>0.33</sub> In <sub>0.51</sub> | 15.2               | 12.1               | 1.8                |
| 1/10         | Mo <sub>0.42</sub> Ge <sub>0.44</sub> Fe <sub>0.53</sub> | 6.3                | 35.1               | 2.2                |
| 1/11         | V <sub>0.47</sub> W <sub>0.19</sub> Ni <sub>0.33</sub>   | 44.6               | 2.3                | 1.0                |
| 1/12         | Mn <sub>0.41</sub> Ga <sub>0.51</sub> Nb <sub>0.08</sub> | 13.1               | 12.7               | 1.7                |

|      |  |      |      |      |
|------|--|------|------|------|
| 1/13 | Mo <sub>0.45</sub> Co <sub>0.22</sub> In <sub>0.33</sub> | 1.0  | 46.5 | 0.5  |
| 1/14 | Fe <sub>0.75</sub> Ge <sub>0.05</sub> W <sub>0.20</sub>  | 16.0 | 12.9 | 2.1  |
| 1/15 | V <sub>0.33</sub> Mn <sub>0.43</sub> Ni <sub>0.23</sub>  | 12.5 | 26.6 | 3.3  |
| 1/16 | Zn <sub>0.67</sub> Nb <sub>0.1</sub> Co <sub>0.23</sub>  | 15.2 | 0.3  | 0.05 |
| 1/17 | Mo <sub>0.33</sub> Fe <sub>0.42</sub> Cd <sub>0.25</sub> | 2.1  | 7.7  | 0.2  |
| 1/18 | Ga <sub>0.01</sub> W <sub>0.33</sub> Ni <sub>0.66</sub>  | 23.6 | 3.3  | 0.8  |
| 1/19 | Mn <sub>0.33</sub> Zn <sub>0.41</sub> In <sub>0.25</sub> | 15.7 | 9.5  | 1.5  |
| 1/20 | Ge <sub>0.14</sub> Co <sub>0.33</sub> Cd <sub>0.53</sub> | 14.6 | 8.6  | 1.3  |

2. Catalyst generation

Step 6. The second generation of catalysts was obtained in that first the four catalysts (No. 4, 8, 10, 15) with the best catalytic behavior were selected and used for further 5 modification.

Step 7. The compositions of the new catalysts 2/21 of the second generation were obtained in a similar way as described in step 7 of example 1, based on K.1/15 and the main component V, then K.1/8 and the main component Ga, then K.1/4 and the 10 main component Cd, then K.1/10 and the minor component Ge. The thus selected components were combined with their original molar amounts to a new catalysts component. In analogy, the catalysts 2/22 to 2/30 of the second generation were obtained. The preparation of the resulting total of 10 new catalysts of the second generation was carried out as that of the first generation (step 2).

Step 8. With the procedure described in step 7, 10 new catalyst compositions were determined, produced according to the procedure (step 3), and then tested parallel under standard conditions as described in step 4 (compare step (e) above). The results are compiled in Table 6.

Table 6. Compositions and Catalytic Results of the Second Generation

| Cat.- No. | Composition  | X(C <sub>3</sub> H <sub>8</sub> ) | S(C <sub>3</sub> H <sub>6</sub> ) | Y(C <sub>3</sub> H <sub>6</sub> ) |
|-----------|--|-----------------------------------|-----------------------------------|-----------------------------------|
|           |  | %                                 | )                                 | %                                 |
| 2/21      | V <sub>0.33</sub> Ga <sub>0.40</sub><br>Cd <sub>0.23</sub> Ge <sub>0.04</sub> O <sub>x</sub> | 2.4                               | 54.0                              | 1.3                               |
| 2/22      | V <sub>0.30</sub> Fe <sub>0.48</sub> Ni <sub>0.21</sub> O <sub>x</sub>                       | 26.1                              | 1.4                               | 0.4                               |
| 2/23      | V <sub>0.30</sub> Fe <sub>0.48</sub> Cd <sub>0.22</sub> O <sub>x</sub>                       | 13.8                              | 20.2                              | 2.8                               |
| 2/24      | V <sub>0.47</sub> Mn <sub>0.22</sub> Ga <sub>0.31</sub> O <sub>x</sub>                       | 17.0                              | 37.0                              | 6.3                               |
| 2/25      | Mo <sub>0.45</sub> Fe <sub>0.25</sub> Ge <sub>0.29</sub> O <sub>x</sub>                      | 0.2                               | 66.9                              | 0.1                               |
| 2/26      | Fe <sub>0.09</sub> Ge <sub>0.33</sub> Ni <sub>0.58</sub> O <sub>x</sub>                      | 16.7                              | 1.8                               | 0.3                               |
| 2/27      | V <sub>0.26</sub> Mo <sub>0.33</sub> Fe <sub>0.41</sub> O <sub>x</sub>                       | 17.4                              | 22.4                              | 3.9                               |
| 2/28      | Ga <sub>0.15</sub> Ge <sub>0.33</sub> Cd <sub>0.52</sub> O <sub>x</sub>                      | 2.7                               | 6.2                               | 0.2                               |
| 2/29      | V <sub>0.43</sub> Mn <sub>0.54</sub> Fe <sub>0.03</sub> O <sub>x</sub>                       | 16.4                              | 34.1                              | 5.6                               |
| 2/30      | V <sub>0.48</sub> Ge <sub>0.19</sub> Ni <sub>0.33</sub> O <sub>x</sub>                       | 43.1                              | 0.4                               | 0.2                               |

3. Catalyst generation

Step 9. From the catalysts of the first and second catalyst generations, four catalysts with the best efficiency were again selected (Nos. 8, 24, 27, 29) (compare step (f) above) and used as a basis for further steps.

Step 10. The composition of 10 new catalysts to be produced of the third generation was obtained in that the same procedure as in step 7 or in step 10 of example 1 was carried out with the four catalysts selected in step 9 (see Table 6, compare step (g) above), based on K.2/19 and the main component V, then K.2/27 and the main component Mo, then K.2/24 and the main component Mn. The thus selected components were combined with their original molar amounts to a new catalyst composition. In analogy, the catalysts 3/52 to 3/60 of the third generation were obtained (Table 7). The preparation of the overall resulting 10 new catalysts of the third generation was carried out in analogy to that of the first and second generations (step 2 and 7).

Step 11. The 10 new catalysts of the third catalyst generation were prepared according to procedure (compare step 3) and tested parallel under standard conditions as described in step 4 (compare step (h) above).

Table 7. Compositions and Catalytic Results of the Third Generation

| Cat.-No. | Compositions  | X(C <sub>3</sub> H <sub>8</sub> )/% | S(C <sub>3</sub> H <sub>6</sub> )/% | Y(C <sub>3</sub> H <sub>6</sub> )/% |
|----------|---|-------------------------------------|-------------------------------------|-------------------------------------|
| 3/51     | V <sub>0.32</sub> Mo <sub>0.41</sub><br>Mn <sub>0.27</sub>                    | 13.6                                | 28.4                                | 3.9                                 |
| 3/52     | V <sub>0.26</sub> Mn <sub>0.33</sub><br>Ga <sub>0.41</sub>                    | 20.4                                | 29.9                                | 6.1                                 |
| 3/53     | V <sub>0.20</sub> Mn <sub>0.17</sub><br>Fe <sub>0.32</sub> Ga <sub>0.32</sub> | 19.7                                | 39.0                                | 7.7                                 |
| 3/54     | V <sub>0.47</sub> Mn <sub>0.13</sub><br>Ga <sub>0.38</sub>                    | 19.8                                | 31.9                                | 6.3                                 |
| 3/55     | V <sub>0.37</sub> Mn <sub>0.22</sub><br>Fe <sub>0.41</sub>                    | 19.2                                | 31.5                                | 6.0                                 |
| 3/56     | Mn <sub>0.15</sub> Fe <sub>0.33</sub><br>Ga <sub>0.52</sub>                   | 13.9                                | 6.7                                 | 0.9                                 |
| 3/57     | V <sub>0.43</sub> Mo <sub>0.54</sub><br>Mn <sub>0.03</sub>                    | 14.8                                | 33.8                                | 5.0                                 |
| 3/58     | Mo <sub>0.48</sub> Fe <sub>0.18</sub><br>Ga <sub>0.33</sub>                   | 2.2                                 | 59.8                                | 1.3                                 |
| 3/59     | V <sub>0.42</sub> Mo <sub>0.52</sub><br>Mn <sub>0.07</sub>                    | 17.6                                | 28.8                                | 5.1                                 |
| 3/60     | V <sub>0.46</sub> Fe <sub>0.21</sub><br>Ga <sub>0.33</sub>                    | 17.4                                | 33.5                                | 5.8                                 |

#### 4. Catalyst generation

Step 12. Four catalysts with the best efficiency were again selected from the catalysts of the first through third catalyst generations (No. 24, 53, 54, 55) (compare step (f) above) and used as a basis for the new catalysts of the fourth generation.

Step 13. The composition of 10 new catalysts to be prepared of the fourth generation was obtained in that with the four catalysts selected in step 12 the same process as in step 7 was carried out (see Table 6, compare step (g) above).

Step 14. The 10 new catalysts of the third catalyst generation were prepared according to procedure (compare step 3) and tested parallel under standard conditions as in step 4 (compare step (h) above).

According to Fig. 2, a significant increase of the propene yield was obtained already in the fourth generation.

Tabelle 8. Compositions and Results of the Fourth  
5 Generation

| Cat.-No. | Compositions  | X(C <sub>3</sub> H <sub>8</sub> ) % | S(C <sub>3</sub> H <sub>6</sub> ) % | Y(C <sub>3</sub> H <sub>6</sub> ) % |
|----------|---|-------------------------------------|-------------------------------------|-------------------------------------|
| 4/71     | V <sub>0.49</sub> Mn <sub>0.13</sub><br>Ga <sub>0.38</sub>                    | 18.6                                | 39.4                                | 7.3                                 |
| 4/72     | V <sub>0.53</sub> Mn <sub>0.14</sub><br>Fe <sub>0.34</sub>                    | 18.8                                | 27.1                                | 5.1                                 |
| 4/73     | V <sub>0.32</sub> Fe <sub>0.27</sub><br>Ga <sub>0.27</sub>                    | 21.7                                | 32.9                                | 7.1                                 |
| 4/74     | V <sub>0.19</sub> Mn <sub>0.24</sub><br>Fe <sub>0.32</sub> Ga <sub>0.25</sub> | 22.3                                | 35.9                                | 8.0                                 |
| 4/75     | V <sub>0.06</sub> Mn <sub>0.02</sub><br>Ga <sub>0.92</sub>                    | 22.2                                | 34.6                                | 7.7                                 |
| 4/76     | Mn <sub>0.5</sub> Fe <sub>0.16</sub><br>Ga <sub>0.33</sub>                    | 21.6                                | 32.6                                | 7.0                                 |
| 4/77     | V <sub>0.42</sub> Mn <sub>0.53</sub><br>Ga <sub>0.04</sub>                    | 9.7                                 | 34.1                                | 3.3                                 |
| 4/78     | V <sub>0.47</sub> Fe <sub>0.19</sub><br>Ga <sub>0.33</sub>                    | 22.2                                | 33.0                                | 7.3                                 |
| 4/79     | V <sub>0.41</sub> Mn <sub>0.51</sub><br>Fe <sub>0.08</sub>                    | 12.6                                | 22.1                                | 2.8                                 |
| 4/80     | V <sub>0.45</sub> Fe <sub>0.22</sub><br>Ga <sub>0.33</sub>                    | 20.9                                | 33.4                                | 7.0                                 |

Table 1

First Catalyst Generation

| No. | Composition mole-% |                 |                  |       |         |         |       |        |          |       | Yield of an<br>C <sub>3</sub> -Oxygenates the 5 best<br>Catalyst<br>- Generations |           |        |                     |       |
|-----|--------------------|-----------------|------------------|-------|---------|---------|-------|--------|----------|-------|---|-----------|--------|---------------------|-------|
|     | Main component     | Minor component | Doping component |       |         |         |       |        |          |       | support weight  | Pd weight | mole-% | Rank among<br>1 2 3 |       |
| 1   | V 13.75            | Mo 6.75         | Nb 0             | Bi 0  | P 16.84 | Sb 9.83 | Sn 0  | B 2.83 | Fe 0,344 | Co 0  | Cs 0  | Ag 0      | Cu 0   | Ga 0                | In 0  |
| 2   | 40,48              | 22,76           | 0                | 5,05  | 30,57   | 0       | 0     | 0      | 0        | 0     | 0   | 0         | 0      | 0                   | 50    |
| 3   | 0                  | 20,85           | 2,97             | 0     | 28,73   | 0       | 10,95 | 23,60  | 0        | 0     | 0   | 0         | 0      | 0                   | 1,137 |
| 4   | 0                  | 15,12           | 4,96             | 0     | 0       | 0       | 19,60 | 9,44   | 0        | 0     | 0,449   | 0         | 0      | 0                   | 0     |
| 5   | 8,59               | 0               | 0                | 0     | 0       | 23,87   | 13,26 | 0      | 2,65     | 0     | 0,887   | 0         | 0      | 0                   | 0,340 |
| 6   | 11,04              | 38,88           | 0                | 19,56 | 0,230   | 0       | 0     | 28,07  | 0,761    | 0     | 0   | 0         | 0      | 0                   | 50    |
| 7   | 0                  | 29,53           | 12,88            | 0     | 36,86   | 20,22   | 0     | 0      | 0        | 0     | 0   | 0         | 0      | 0                   | 0     |
| 8   | 11,96              | 38,26           | 0                | 0     | 20,00   | 0       | 1,74  | 28,04  | 0        | 0     | 0   | 0         | 0      | 0                   | 0     |
| 9   | 0                  | 9,09            | 22,49            | 0     | 0       | 0       | 13,19 | 3,88   | 0        | 0,463 | 0   | 0,748     | 0,262  | 0                   | 0     |
| 10  | 10,14              | 0               | 1,54             | 13,93 | 0       | 0       | 5,33  | 0      | 17,72    | 0,218 | 0   | 0,305     | 0      | 0,467               | 0,763 |
| 11  | 0                  | 0               | 6,09             | 0     | 0       | 29,09   | 0     | 13,12  | 1,232    | 0     | 0,410   | 0,987     | 0      | 0                   | 0,427 |
| 12  | 0                  | 0               | 18,37            | 6,77  | 0       | 0       | 0     | 23,48  | 0,287    | 0     | 0,398   | 0,607     | 0      | 0                   | 0,986 |
| 13  | 0                  | 6,69            | 34,53            | 0     | 0       | 0       | 0     | 15,20  | 43,04    | 0     | 0   | 0,548     | 0      | 0                   | 0     |
| 14  | 0                  | 11,33           | 4,54             | 0     | 14,33   | 7,53    | 0,73  | 0      | 10,53    | 0,321 | 0   | 0,668     | 0,226  | 0                   | 0,343 |
| 15  | 0                  | 20,09           | 11,40            | 0     | 0       | 0       | 2,70  | 15,23  | 0        | 0     | 0,582   | 0         | 0      | 0                   | 50    |
| 16  | 10,37              | 1,67            | 0                | 14,20 | 5,50    | 0       | 0     | 18,04  | 0        | 0     | 0,222   | 0         | 0      | 0                   | 0     |
| 17  | 8,56               | 2,90            | 0                | 11,06 | 5,40    | 0       | 0     | 13,55  | 7,89     | 0     | 0   | 0,198     | 0      | 0,435               | 0,166 |
| 18  | 14,11              | 0               | 5,89             | 17,74 | 0       | 0       | 9,51  | 1,28   | 0        | 0,318 | 0   | 0,495     | 0,640  | 0                   | 0,340 |
| 19  | 0                  | 9,11            | 0                | 23,40 | 13,48   | 0       | 0     | 3,56   | 0        | 0     | 0,466   | 0         | 0      | 0                   | 50    |
| 20  | 27,10              | 15,00           | 0                | 2,90  | 20,33   | 0       | 0     | 8,23   | 25,66    | 0     | 0   | 0,318     | 0      | 0,452               | 0,700 |
| 21  | 0                  | 0               | 0,187            | 0     | 18,58   | 5,69    | 0     | 0      | 24,25    | 0     | 1,069   | 0,393     | 0      | 0                   | 0     |
| 22  | 0                  | 0               | 29,61            | 12,82 | 0       | 37,00   | 20,21 | 0      | 0        | 0     | 0,363   | 0         | 0,939  | 0                   | 0     |
| 23  | 0                  | 0               | 39,59            | 0     | 3,10    | 55,66   | 0     | 0      | 0        | 0     | 1,652   | 0         | 0      | 0,346               | 0     |
| 24  | 20,70              | 5,98            | 0                | 27,18 | 12,47   | 33,67   | 0     | 0      | 0        | 0     | 0   | 0         | 0      | 0                   | 0     |
| 25  | 0                  | 0               | 0                | 31,94 | 7,13    | 0       | 42,87 | 18,06  | 0        | 1,723 | 0   | 0         | 0      | 0,474               | 0     |
| 26  | 11,51              | 0               | 38,74            | 19,84 | 0       | 0       | 0     | 0,94   | 28,17    | 0     | 0   | 0,801     | 0      | 0                   | 0     |
| 27  | 6,69               | 17,04           | 0                | 9,85  | 2,67    | 0       | 0     | 13,02  | 0        | 0     | 0,531   | 0         | 0      | 0,208               | 50    |
| 28  | 22,58              | 9,24            | 0                | 0     | 28,46   | 15,12   | 0     | 1,77   | 21,00    | 0     | 0,659   | 0,328     | 0      | 0,454               | 0,691 |
| 29  | 0                  | 0               | 19,95            | 0     | 11,41   | 0       | 2,87  | 15,17  | 0        | 0     | 0   | 0,597     | 0      | 0,240               | 0     |
| 30  | 29,36              | 11,64           | 0                | 37,17 | 19,45   | 0       | 0     | 1,73   | 0        | 0     | 0,649   | 0         | 0      | 1,001               | 0     |

Table 2

Second Catalyst Generation

| No. | Composition mole-% |       |       |       |       |                  |       |       |      |       | support weight % | Pd weight % | Yield of an C <sub>3</sub> -Oxygenates mole-% | Rank among the 5 best Catalyst Generations 2 3 |       |        |        |        |       |
|-----|--------------------|-------|-------|-------|-------|------------------|-------|-------|------|-------|------------------|-------------|---|--|-------|--------|--------|--------|-------|
|     | Minor component    |       |       |       |       | Doping component |       |       |      |       |                  |             |   |  |       |        |        |        |       |
| V   | Mo                 | Nb    | Bi    | P     | Mn    | Sb               | Sn    | B     | Fe   | Co    | Cs               | Ag          | Cu  | Ga   | In    |        |        |        |       |
| 1   | 0                  | 0     | 8.54  | 14.34 | 0     | 0                | 7.28  | 18.72 | 0.83 | 0.825 | 0.303            | 0           | 0   | 0  | 50    | 0.0001 | 0.037  |        |       |
| 2   | 0                  | 10.82 | 0     | 22.07 | 0     | 0                | 16.10 | 0     | 0.55 | 0.553 | 0.467            | 0           | 0   | 0  | 50    | 0.0001 | 0.184  |        |       |
| 3   | 0                  | 15.47 | 0     | 19.01 | 0     | 0                | 13.87 | 0     | 0    | 0.908 | 0.402            | 0           | 0   | 0  | 50    | 0      | 0.161  |        |       |
| 4   | 0                  | 2.87  | 15.14 | 0     | 0     | 0                | 26.50 | 4.22  | 0    | 0     | 0.738            | 0           | 0   | 0  | 50    | 0.0001 | 0.001  |        |       |
| 5   | 0                  | 11.79 | 0     | 11.48 | 1.35  | 0                | 0     | 24.43 | 0    | 0     | 0.952            | 0           | 0   | 0  | 50    | 0.0001 | 0.024  |        |       |
| 6   | 0                  | 4.37  | 3.24  | 7.22  | 12.13 | 0                | 12.80 | 9.93  | 0    | 0.300 | 0                | 0           | 0   | 0  | 50    | 0.0001 | 0.020  |        |       |
| 7   | 0                  | 0     | 0     | 26.54 | 0     | 0                | 21.71 | 0     | 0    | 1.270 | 0                | 0           | 0   | 0  | 50    | 0.0001 | 0.024  |        |       |
| 8   | 6.42               | 6.82  | 0     | 0     | 13.92 | 4.27             | 0     | 11.39 | 5.91 | 0     | 0.670            | 0.150       | 0   | 0.330  | 0.120 | 0      | 50     | 0.0001 | 0.000 |
| 9   | 0                  | 4.04  | 9.23  | 0     | 0     | 0                | 20.15 | 13.75 | 0    | 0     | 2.090            | 0           | 0   | 0.740  | 0     | 50     | 0.0001 | 0.003  |       |
| 10  | 0                  | 3.09  | 0     | 26.10 | 5.85  | 0                | 0     | 13.69 | 0    | 0     | 1.270            | 0           | 0   | 0  | 50    | 0.0001 | 0.000  |        |       |

Table 3

third Catalyst Generation

| No. | Composition mole-% |       |       |       |       |                 |       |       |      |      | Doping component |             |             |             | support weight % |             |             |  | Rank among the 5 best Catalyst - Generations |
|-----|--------------------|-------|-------|-------|-------|-----------------|-------|-------|------|------|------------------|-------------|-------------|-------------|------------------|-------------|-------------|--|--|
|     | Minor component    |       |       |       |       | Major component |       |       |      |      | Pd weight %      | Pd weight % | Pd weight % | Pd weight % | Pd weight %      | Pd weight % | Pd weight % | Pd weight %                                  |  |
| V   | Mo                 | Nb    | Bi    | P     | Mn    | Sb              | Sn    | B     | Fe   | Co   | Cs               | Ag          | Cu          | Ga          | In               | %           | mole-%      | Rank among the 5 best Catalyst - Generations |  |
| 1   | 0                  | 31.78 | 0     | 17.10 | 0     | 0               | 0     | 0     | 0.82 | 0    | 0                | 0.31        | 0           | 50          | 0.0001           | 0.006       | 2.          |  |  |
| 2   | 0                  | 6.34  | 24.05 | 0     | 12.94 | 0               | 0     | 5.50  | 0    | 0.62 | 0.14             | 0           | 0.30        | 0.12        | 0                | 50          | 0.0001      | 0.096  |  |
| 3   | 0                  | 6.40  | 14.62 | 9.90  | 0     | 0               | 0     | 18.22 | 0    | 0.38 | 0.23             | 0           | 0.12        | 0.07        | 0                | 50          | 0           | 0.010  |  |
| 4   | 0                  | 34.61 | 0.87  | 0     | 0     | 5.37            | 8.28  | 0     | 0    | 0.43 | 0                | 0           | 0.07        | 0.45        | 0                | 50          | 0.0001      | 0.821  |  |
| 5   | 0                  | 19.45 | 0     | 13.27 | 2.67  | 0               | 0     | 13.64 | 0    | 0    | 0.96             | 0           | 0           | 0.45        | 0                | 0           | 50          | 0.0001                                       | 0.035  |
| 6   | 0                  | 5.94  | 4.40  | 9.82  | 0     | 0               | 17.40 | 12.03 | 0    | 0    | 0.41             | 0           | 0           | 0           | 0                | 0           | 50          | 0.0001                                       | 0.000  |
| 7   | 0                  | 0     | 7.47  | 0     | 20.29 | 0               | 0     | 20.40 | 0    | 0    | 1.34             | 0           | 0           | 0.51        | 0                | 50          | 0.0001      | 0.050  |  |
| 8   | 0                  | 8.70  | 4.74  | 0     | 12.88 | 0               | 0     | 14.53 | 7.54 | 0    | 0.85             | 0.19        | 0           | 0.51        | 0.16             | 0           | 50          | 0  | 0.161  |
| 9   | 0                  | 17.74 | 4.63  | 0     | 0     | 15.86           | 10.15 | 0     | 0    | 0.43 | 0                | 0           | 0.16        | 1.20        | 0                | 50          | 0.0001      | 0.965  |  |
| 10  | 0                  | 1.66  | 0     | 31.55 | 7.22  | 0               | 0     | 9.00  | 0    | 0    | 0.56             | 0           | 0           | 1.20        | 0                | 0           | 50          | 0.0001                                       | 0.063  |